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DescriptionBATTERY INCLUDING CARBON FOAM CURRENT COLLECTORSTechnical Field

- [01] This invention relates generally to current collectors for a battery and, more particularly, to carbon foam current collectors for a lead acid battery.

Background

- [02] Lead acid batteries are known to include at least one positive current collector, at least one negative current collector, and an electrolytic solution including, for example, sulfuric acid ( $H_2SO_4$ ) and distilled water. Ordinarily, both the positive and negative current collectors in a lead acid battery are constructed from lead. The role of these lead current collectors is to transfer electric current to and from the battery terminals during the discharge and charging processes. Storage and release of electrical energy in lead acid batteries is enabled by chemical reactions that occur in a paste disposed on the current collectors. The positive and negative current collectors, once coated with this paste, are referred to as positive and negative plates, respectively. A notable limitation on the durability of lead-acid batteries is corrosion of the lead current collector of the positive plate.
- [03] The rate of corrosion of the lead current collector is a major factor in determining the life of the lead-acid battery. Once the sulfuric acid electrolyte is added to the battery and the battery is charged, the current collector of each positive plate is continually subjected to corrosion due to its exposure to sulfuric acid and to the anodic potentials of the positive plate. One of the most damaging effects of this corrosion of the positive plate current collector is volume expansion. Particularly, as the lead current collector corrodes, lead dioxide is formed from the lead source metal of the current collector. Moreover, this lead dioxide corrosion product has a greater volume than the lead source material

consumed to create the lead dioxide. Corrosion of the lead source material and the ensuing increase in volume of the lead dioxide corrosion product is known as volume expansion.

[04] Volume expansion induces mechanical stresses on the current collector that deform and stretch the current collector. At a total volume increase of the current collector of approximately 4% to 7%, the current collector may fracture. As a result, battery capacity may drop, and eventually, the battery will reach the end of its service life. Additionally, at advanced stages of corrosion, internal shorting within the current collector and rupture of the cell case may occur. Both of these corrosion effects may lead to failure of one or more of the cells within the battery.

[05] One method of extending the service life of a lead acid battery is to increase the corrosion resistance of the current collector of the positive plate. Several methods have been proposed for inhibiting the corrosion process in lead acid batteries. Because carbon does not oxidize at the temperatures at which lead-acid batteries generally operate, some of these methods have involved using carbon in various forms to slow or prevent the detrimental corrosion process in lead acid batteries. For example, U.S. Patent No. 5,512,390 (hereinafter the '390 patent) discloses a lead acid battery that includes current collectors made from graphite plates instead of lead. The graphite plates have sufficient conductivity to function as current collectors, and they are more corrosion resistant than lead. Substituting graphite plates for the lead current collectors may, therefore, lengthen the life of a lead-acid battery.

[06] While the battery of the '390 patent may potentially offer a lengthened service life as a result of reduced corrosion at the positive plate, the graphite plates of the '390 patent are problematic. For example, the graphite plates of the '390 patent are dense, flat sheets of material each having a relatively small amount of surface area. Unlike lead electrode plates of a conventional lead-acid battery, which are generally patterned into a grid-like structure to

increase the available surface area of the plates, the graphite plates of the '390 patent are smooth sheets with no patterning. In lead acid batteries, an increase in surface area of the current collector may increase the specific energy of the battery and, therefore, may translate into improved battery performance. More surface area on the current collectors may also lead to a reduction in the time required for charging and discharging of the battery. The relatively small surface area of the graphite plates of the '390 patent results in poorly performing batteries that have slow charging speeds.

[07]                Additionally, the graphite plates of the '390 patent lack the toughness of lead current collectors. The dense, graphite plates of the '390 patent are brittle and may fracture when subjected to physical shock or vibration. Such physical shock and vibration commonly occur in vehicular applications, for example. Any fracturing of the graphite plates would lead to the same problems caused by volume expansion of ordinary lead current collectors. Therefore, despite offering an increased resistance to corrosion compared to conventional lead current collectors, the brittle nature of the graphite plates of the '390 patent could actually result in battery service lives shorter than those possible through use of ordinary lead current collectors.

[08]                The present invention is directed to overcoming one or more of the problems or disadvantages existing in the prior art.

#### Summary of the Invention

[09]                One aspect of the present invention includes an electrode plate for a battery. The electrode plate includes a carbon foam current collector that has a network of pores. A chemically active paste is disposed on the carbon foam current collector such that the chemically active paste penetrates into the network of pores.

[10]                A second aspect of the present invention includes a method of making an electrode plate for a lead acid battery. This method includes forming a current collector from carbon foam. The carbon foam current collector includes a

protruding tab and a network of pores. An electrical connection is then formed at the protruding tab of the current collector. The method also includes applying a chemically active paste to the current collector such that the chemically active paste penetrates the network of pores in the carbon foam.

- [11] A third aspect of the present invention includes a lead-acid battery. This battery includes a housing, and positive and negative terminals external to the housing. Within the housing is at least one cell that includes at least one positive plate and at least one negative plate connected to the positive terminal and negative terminal, respectively. An electrolytic solution fills a volume between the positive and negative plates. The at least one positive plate includes a carbon foam current collector including a network of pores, and a chemically active paste disposed on the carbon foam current collector such that the chemically active paste penetrates the network of pores

#### Brief Description of the Drawings

- [12] The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate exemplary embodiments of the invention and, together with the written description, serve to explain the principles of the invention. In the drawings:
- [13] Fig. 1 is a diagrammatic cut-away representation of a battery in accordance with an exemplary embodiment of the present invention;
- [14] Figs. 2A and 2B are photographs of a current collector in accordance with an exemplary embodiment of the present invention;
- [15] Fig. 3 is a photograph of the porous structure of a carbon foam current collector, at about 10x magnification, in accordance with an exemplary embodiment of the present invention; and
- [16] Fig. 4 is a diagrammatic, close-up representation of the porous structure of a carbon foam current collector in accordance with an exemplary embodiment of the present invention.

### Detailed Description

- [17] In the following description, reference is made to the accompanying drawings that form a part thereof, and in which is shown by way of illustration specific exemplary embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention, and it is to be understood that other embodiments may be utilized and that changes may be made without departing from the scope of the present invention. The following description is, therefore, not to be taken in a limited sense. Wherever possible, the same reference numbers are used throughout the drawings to refer to the same or like parts.
- [18] Fig. 1 illustrates a battery 10 in accordance with an exemplary embodiment of the present invention. Battery 10 includes a housing 11 and terminals 12, which are external to housing 11. At least one cell 13 is disposed within housing 11. While only one cell 13 is necessary, multiple cells may be connected in series to provide a desired total potential of battery 10.
- [19] Each cell 13 may be composed of alternating positive and negative plates immersed in an electrolytic solution including, for example, sulfuric acid and distilled water. Both the positive and negative plates include a current collector packed with a paste material, including, for example, an oxide of lead. Fig. 2A illustrates a current collector 20 according to an exemplary embodiment of the present invention. Current collector 20 includes a thin, rectangular body and a tab 21 used to form an electrical connection with current collector 20.
- [20] The current collector shown in Fig. 2A may be used to form either a positive or a negative plate. As previously stated, chemical reactions in the paste disposed on the current collectors of the battery enable storage and release of energy. The composition of this paste, and not the material selected for the current collector, determines whether a given current collector functions as either a positive or a negative plate.

[21] While the type of plate, whether positive or negative, does not depend on the material selected for current collector 20, the current collector material and configuration affects the characteristics and performance of battery 10. For example, during either the charging and discharging processes, each current collector 20 transfers the resulting electric current to and from battery terminals 12. In order to efficiently transfer current to and from terminals 12, current collector 20 must be formed from a conductive material. Additionally, the susceptibility of the current collector material to corrosion will affect not only the performance of battery 10, but it will also impact the service life of battery 10. In addition to the material selected for the current collector 20, the configuration of current collector 20 is also important to battery performance. For instance, the amount of surface area available on current collector 20 influences both the specific energy and the charge/discharge rates of the battery 10.

[22] In an exemplary embodiment of the present invention, current collector 20, as shown in Fig. 2A, is formed from of a porous, carbon foam material. Because the foam is carbon, it resists corrosion even when exposed to sulfuric acid and to the anodic potentials of the positive plate. The carbon foam includes a network of pores, which provides a large amount of surface area for each current collector 20. Current collectors composed of carbon foam may exhibit more than 2000 times the amount of surface area provided by conventional lead current collectors. Fig. 2B illustrates a closer view of tab 21 formed on current collector 20. Tab 21 may be coated with a conductive material and used to form an electrical connection with the current collector 20. The conductive material used to coat tab 21 may include a metal that is more conductive than the carbon foam current collector. Coating tab 21 with a conductive material provides structural support for tab 21 and creates a suitable electrical connection capable of handling the high currents present in a lead acid battery.

[23] Fig. 3 provides a view of current collector 20, including the network of pores, at approximately 10x magnification. Fig. 4 provides an even more detailed representation (approximately 100x magnification) of the network of pores. The carbon foam of the exemplary embodiment includes from about 4 to about 50 pores per centimeter, and a total porosity value for the carbon foam may be at least 60%. In other words, at least 60% of the volume of the carbon foam structure is included within pores 41. Moreover, the carbon foam may have an open porosity value of at least 90%. Therefore, at least 90% of pores 41 are open to adjacent pores such that the network of pores 41 forms a substantially open network. This open network of pores 41 allows the paste deposited on each current collector 20 to penetrate within the carbon foam structure. In addition to the network of pores 41, the carbon foam includes a web of structural elements 42 that provide support for the carbon foam. Combined, the network of pores 41 and the structural elements 42 of the carbon foam result in a density of less than about  $0.6 \text{ gm/cm}^3$  for the carbon foam material.

[24] Due to the high conductivity of the carbon foam of the present invention, current collectors 20 efficiently transfer current to and from the battery terminals 12. In certain forms, the carbon foam may offer sheet resistivity values of less than about 1 ohm/cm. In still other forms, the carbon foam may have sheet resistivity values of less than about 0.75 ohm/cm

[25] In addition to carbon foam, graphite foam may also be used to form current collector 20. One such graphite foam, under the trade name PocoFoam™, is available from Poco Graphite, Inc. The density and pore structure of graphite foam may be similar to carbon foam. A primary difference between graphite foam and carbon foam is the orientation of the carbon atoms that make up the structural elements 42. For example, in carbon foam, the carbon may be primarily amorphous. In graphite foam, however, much of the carbon is ordered into a graphite, layered structure. Because of the ordered nature of the graphite structure, graphite foam offers higher conductivity than carbon foam.



PocoFoam™ graphite foam exhibits electrical resistivity values of between about 100  $\mu\Omega/\text{cm}$  and about 400  $\mu\Omega/\text{cm}$ .

[26] In an exemplary embodiment of the present invention, current collector 20 may be made from either carbon foam or from graphite foam. Because corrosion affects primarily current collector 20 of the positive plate, however, the current collector of the negative plate may be formed of a material other than carbon or graphite foam. For example, the current collector of the negative plate may be made of lead or another suitable conductive material.

[27] The process for making an electrode plate for a lead acid battery according to the present invention begins by forming current collector 20. To form current collector 20, a block of carbon foam may be machined into thin sheets. While any form of mechanical machining, such as, for example, band sawing, may be used to form thin sheets of carbon foam, wire EDM (electrical discharge machining) provides a method that better preserves the open-cell structure of the carbon foam. In wire EDM, conductive materials are cut with a thin wire surrounded by de-ionized water. There is no physical contact between the wire and the part being machined. Rather, the wire is rapidly charged to a predetermined voltage, which causes a spark to bridge a gap between the wire and the work piece. As a result, a small portion of the work piece melts. The de-ionized water then cools and flushes away the small particles of the melted work piece. Because no cutting forces are generated by wire EDM, the carbon foam of the present invention may be machined without causing the network of pores 41 to collapse. By preserving pores 41 on the surface of the current collector, chemically active paste may penetrate more easily into current collector 20.

[28] As shown in Fig. 2A, current collector 20 includes tab 21, which is used to form an electrical connection to current collector 20. The electrical connection of current collector 20 may be required to carry currents of up to about 100 amps or even greater. In order to form an appropriate electrical connection capable of carrying such currents, the carbon foam that forms tab 21

may be pre-treated by a method that causes a conductive material, such as a metal, to wet the carbon foam. Such methods may include, for example, electroplating and thermal spray techniques. While both of these techniques may be suitable, thermal spray may offer the added benefit of enabling the conductive metal to penetrate deeper into the porous network of the carbon foam. In an exemplary embodiment of the present invention, silver may be applied to tab 21 by thermal spray to form a carbon-metal interface. In addition to silver, other conductive materials may be used to form the carbon-metal interface depending on a particular application.

[29]                Once a carbon-metal interface has been established at tab 21, a second conductive material may be added to the tab 21 to complete the electrical connection. For example, a metal such as lead may be applied to tab 21. In an exemplary embodiment, lead wets the silver-treated carbon foam in a manner that allows enough lead to be deposited on tab 21 to form a suitable electrical connection.

[30]                After forming the electrical connection at tab 21, a chemically active paste is applied to current collector 20 such that the chemically active paste penetrates the network of pores in the carbon foam. One exemplary method for applying the chemically active paste to current collector 20 includes spreading the paste onto a transfer sheet, folding the transfer sheet including the paste over the current collector 20, and applying pressure to the transfer sheet to force the chemically active paste into pores 41. Pressure for forcing the paste into pores 41 may be applied by a roller, mechanical press, or other suitable device.

[31]                Initially, the chemically active paste that is applied to the current collectors 20 of both the positive and negative plates may be substantially the same in terms of chemical composition. For example, the paste may include lead oxide (PbO). Other oxides of lead may also be suitable. The paste may also include various additives including, for example, varying percentages of free lead, structural fibers, conductive materials, carbon, and extenders to

accommodate volume changes over the life of the battery. In practice, the constituents of the chemically active paste may be mixed with a small amount of sulfuric acid and water to form a paste that may be disposed within pores 41 of the current collector 20.

[32]                Once the paste has been deposited on the current collectors 20, the positive and negative plates are formed. To create a positive plate, a current collector 20 including lead oxide paste, for example, is subjected to a curing process. This curing process may include exposing the pasted current collector 20 to elevated temperature and humidity to encourage growth of lead sulfate crystals within the paste. To create the negative plate, however, the current collector 20 including the lead oxide paste may be left "as is", with the exception of an optional step of drying.

[33]                When the positive and negative plates have been assembled together to form the cells of a battery 10 (shown in Fig. 1), the battery 10 is subjected to a charging (i.e., formation) process. During this charging process, the cured paste of the positive plate is electrically driven to lead dioxide ( $\text{PbO}_2$ ), and the paste of the negative plate is converted to sponge lead. Conversely, during subsequent discharge of the battery 10, the pastes of both positive and negative plates convert toward lead sulfate.

#### Industrial Applicability

[34]                By incorporating carbon into the electrode plates of the battery 10 of the present invention, corrosion of the current collector 20 of the positive electrode plate may be suppressed. As a result, the battery of the present invention may offer significantly longer service lives.

[35]                Additionally, the large amount of surface area associated with the carbon foam or graphite foam materials forming current collectors 20 translates into batteries having large specific energy values. Specifically, because of the open cell, porous network and relatively small pore size of the carbon foam

materials, the chemically active paste of the positive and negative plates is intimately integrated with the current collectors 20. The reaction sites in the chemically active paste are close to one or more conductive, carbon foam structural elements 42. Therefore, electrons produced in the chemically active paste at a particular reaction site must travel only a short distance through the paste before encountering one of the many highly conductive structural elements 42 of the current collector 20. As a result, batteries with carbon foam current collectors 20 may offer improved specific energy values. In other words, these batteries, when placed under a load, may sustain their voltage above a predetermined threshold value for a longer time than batteries including either lead current collectors or graphite plate current collectors.

[36] The increased specific energy values offered by batteries of the present invention also translate into reduced charging times. Therefore, the batteries of the present invention may be suitable for applications in which charging energy is available for only a limited amount of time. For instance, in vehicles, a great deal of energy is lost during ordinary braking. This braking energy may be recaptured and used to charge a battery of, for example, a hybrid vehicle. The braking energy, however, is available only for a short period of time (i.e., while braking is occurring). Thus, any transfer of braking energy to a battery must occur during braking. In view of their reduced charging times, the batteries of the present invention may provide an efficient means for storing such braking energy.

[37] Additionally, the carbon foam current collectors of the present invention are pliable, and therefore, they may be less susceptible to damage from vibration or shock as compared to current collectors made from graphite plates or other brittle materials. Therefore, batteries including carbon foam current collectors may perform well in vehicular applications, or other applications, where vibration and shock are common.

[38] Further, by including carbon foam current collectors having a density of less than about  $0.6 \text{ g/cm}^3$ , the battery of the present invention may weigh substantially less than batteries including either lead current collectors or graphite plate current collectors. Other aspects and features of the present invention can be obtained from a study of the drawings, the disclosure, and the appended claims.

Claims

What is claimed is:

1. An electrode plate for a battery, comprising:  
a carbon foam current collector including a network of pores, and  
a chemically active paste disposed on the carbon foam current collector such that the chemically active paste penetrates into the network of pores.
2. The electrode plate of claim 1, wherein the chemically active paste includes an oxide of lead.
3. The electrode plate of claim 1, wherein the carbon foam current collector has a total porosity value of at least 60%.
4. The electrode plate of claim 1, wherein the carbon foam current collector has an open porosity value of at least 90%.
5. The electrode plate of claim 1, wherein the carbon foam current collector has an electrical resistivity value of less than about 1  $\Omega$ /cm.
6. The electrode plate of claim 1, wherein the carbon foam current collector is graphite foam.
7. The electrode plate of claim 6, wherein the graphite foam current collector has an electrical resistivity value of between about 100  $\mu\Omega$ /cm and about 400  $\mu\Omega$ /cm.

8. The electrode plate of claim 1, wherein the carbon foam current collector has a density of less than about  $0.6 \text{ g/cm}^3$ .

9. A method of making an electrode plate for a battery comprising:

forming a current collector from carbon foam, wherein the current collector includes a tab, and the carbon foam includes a network of pores;  
forming an electrical connection at the tab of the current collector;  
applying a chemically active paste to the current collector such that the chemically active paste penetrates the network of pores in the carbon foam.

10. The method of claim 9, wherein the step of forming the electrical connection further includes:

applying a first conductive material to the tab, and  
applying a second conductive material to the first conductive material.

11. The method of claim 10, wherein the first conductive material includes silver and is applied to the tab in the form of a thermal spray.

12. The method of claim 10, wherein the second conductive material includes lead.

13. The method of claim 9, wherein the step of forming the current collector further includes machining the carbon foam using wire EDM.

14. The method of claim 9, wherein the carbon foam current collector has a total porosity value of at least 60 % and an open porosity value of at least 90 %.

15. The method of claim 9, wherein the carbon foam current collector has an electrical resistivity value of less than about 1  $\Omega$ /cm.

16. The method of claim 9, wherein the carbon foam current collector is graphite foam.

17. The method of claim 16, wherein the graphite foam current collector has an electrical resistivity value of between about 100  $\mu\Omega$ /cm and about 400  $\mu\Omega$ /cm.

18. A lead-acid battery comprising:  
a housing;  
a positive terminal and a negative terminal external to the housing;  
at least one cell disposed within the housing and including at least one positive plate and at least one negative plate connected to the positive terminal and negative terminal, respectively; and  
an electrolytic solution filling a volume between the positive and negative plates;  
wherein the at least one positive plate further includes  
a carbon foam current collector including a network of pores, and  
a chemically active paste disposed on the carbon foam current collector such that the chemically active paste penetrates the network of pores.



19. The lead-acid battery of claim 18, wherein the carbon foam current collector has a total porosity value of at least 60% and an open porosity value of at least 90%.

20. The lead-acid battery of claim 18, wherein the carbon foam current collector has an electrical resistivity value of less than about 1  $\Omega/\text{cm}$ .

21. The lead-acid battery of claim 18, wherein the carbon foam current collector includes graphite foam and has an electrical resistivity value of between about 100  $\mu\Omega/\text{cm}$  and about 400  $\mu\Omega/\text{cm}$ .

22. The lead-acid battery of claim 18, wherein the carbon foam current collector has a density of less than about 0.6  $\text{g}/\text{cm}^3$ .

23. The lead-acid battery of claim 18, wherein the at least one negative plate further includes a carbon foam current collector including a network of pores, and a chemically active paste disposed on the carbon foam current collector of the negative plate such that the chemically active paste penetrates the network of pores.

24. A lead-acid battery comprising:  
a housing;  
a positive terminal and a negative terminal external to the housing;  
a plurality of cells connected in series between the positive terminal and the negative terminal;  
a plurality of positive plates disposed in alternating series with a plurality of negative plates within each of the plurality of cells; and  
an electrolytic solution disposed within the housing and filling a volume between adjacent pairs of positive and negative plates;

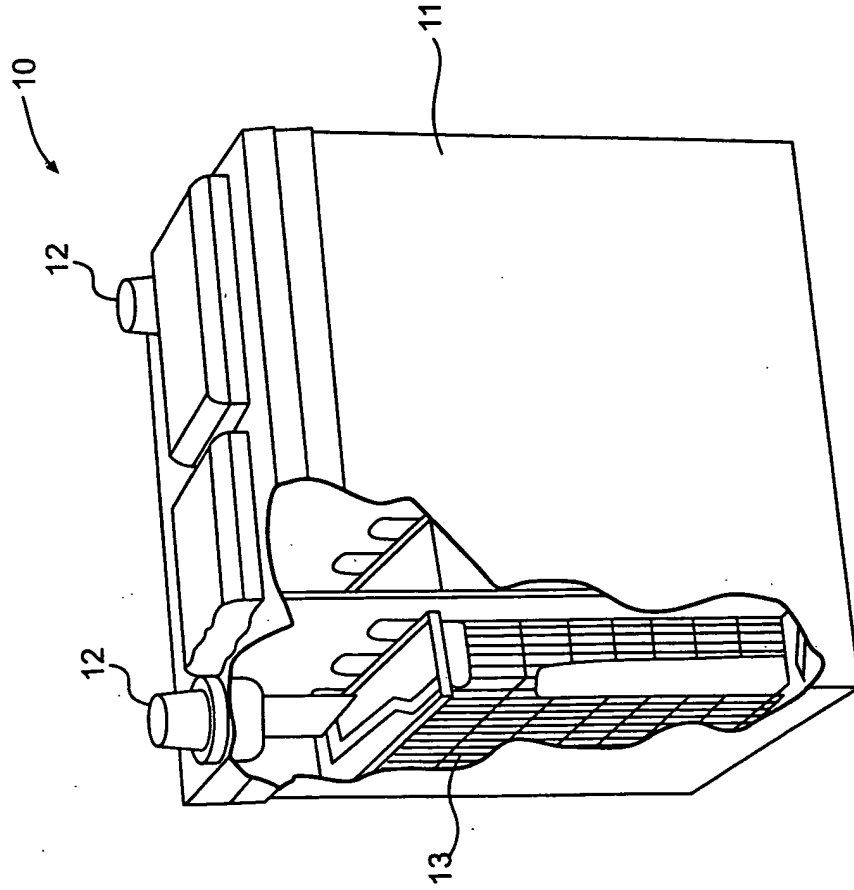
wherein both the plurality of positive plates and the plurality of negative plates further include carbon foam current collectors each including a network of pores, and chemically active paste disposed on the carbon foam current collectors such that the chemically active paste penetrates the network of pores, and

wherein the carbon foam current collectors of both the positive and negative plates each include a tab of carbon foam coated with a conductive metal material configured to make electrical connections to the current collectors of both the positive and negative plates.

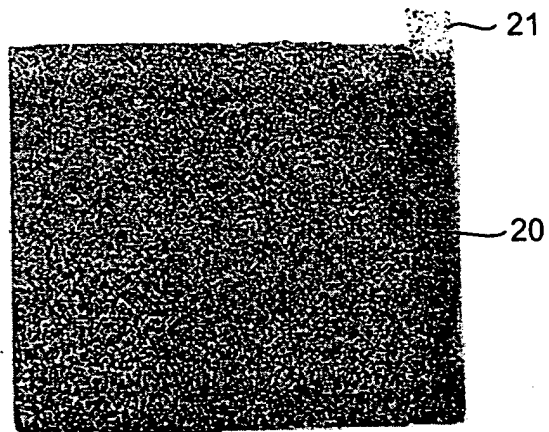
Abstract of the Disclosure

BATTERY INCLUDING CARBON FOAM CURRENT COLLECTORS

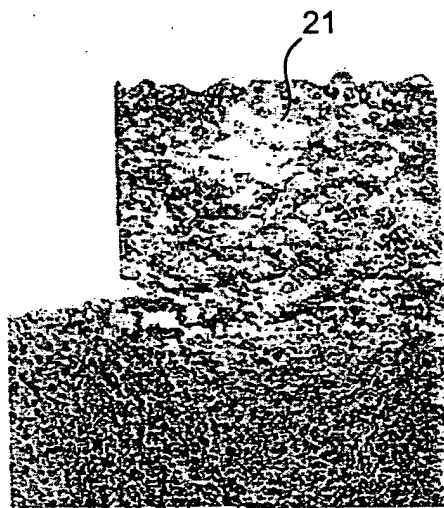
A battery having a current collector constructed of carbon foam. The carbon foam includes a network of pores into which a chemically active paste is disposed to create either a positive or negative plate for the battery. The carbon foam resists corrosion and exhibits a large amount of surface area. The invention includes a method for making the disclosed carbon foam current collector used in the battery.



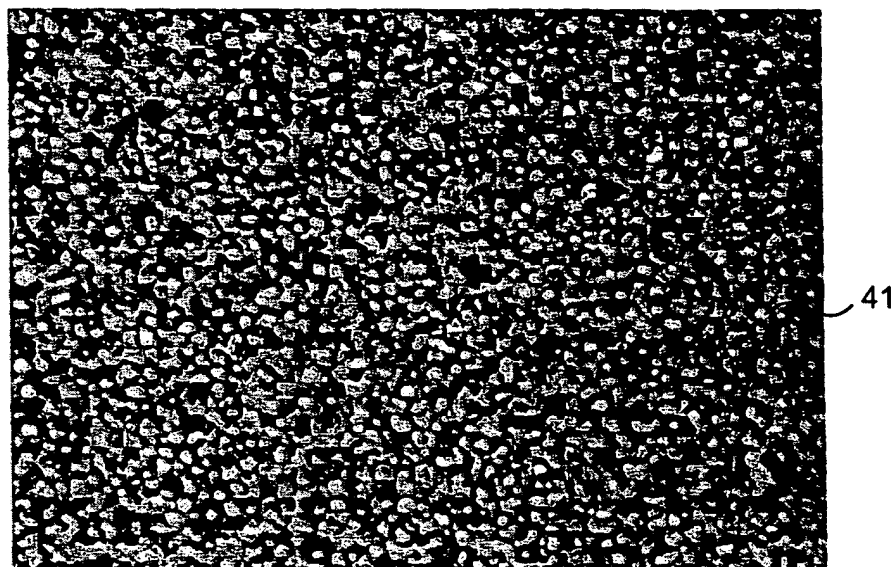
**FIG. 1**



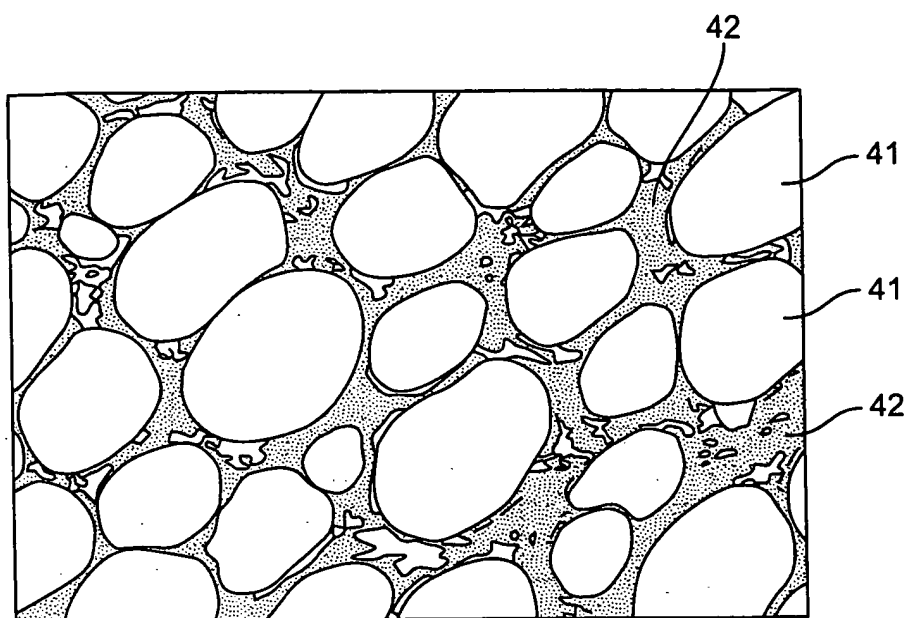
**FIG. 2A**



**FIG. 2B**



***FIG. 3***



**FIG. 4**